REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1993

3. REPORT TYPE AND DATES COVERED
Proceedings, article 1992–1993

4. TITLE AND SUBTITLE Acoustic Scattering into Shadow Zones from Atmospheric Turbulence

5. FUNDING NUMBERS
DA PR: N/A
PE: N/A

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
ARL PR: N/A
AMS code: N/A
Published in Proceedings of the Fourth Annual Ground Target Modeling and Validation Conference, held in August 1993.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

When acoustic scattering estimates are desired from atmospheric regions containing fully developed isotropic homogeneous turbulence, scattering formulas based upon statistical representations of the turbulence well represent the experimental results. However, there is a class of battlefield scenarios where these provisos of fully developed, isotropic and homogeneous sometimes do not apply. The example of this class that is most familiar is that of source and detector near the ground. At ground level, the wind velocity is zero, while at altitude it is not. Thus a gradient of wind velocity exists. There exists often a temperature gradient caused by heating or cooling of the air by contact with the ground. These gradients are recognized in propagation codes by modeling the atmosphere as stratified with each stratum bounded by planes parallel to the assumed flat ground. The anisotropy of the atmosphere near the ground recognized in propagation codes carries over into the generation of turbulence. The above discussion leads to the conclusion that anisotropy in turbulence is to be expected in scenarios played out near the ground, scenarios common to Army operations. The understanding that high sound levels in shadow zones (those regions in an acoustical field in which no sound can reach if the field is determined by ray theory) is caused by scattering from turbulence is very important. This importance arises from the possibility that shadow zone sensors may be used to achieve passive non-line-of-sight detection of enemy assets. This paper unites the above considerations by calculating the shadow zone signal level for a representative battlefield scenario using a structural model of turbulence.

14. SUBJECT TERMS
Acoustic scattering, shadow zones, structural model

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

ACOUSTIC SCATTERING INTO SHADOW ZONES FROM ATMOSPHERIC TURBULENCE

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ABSTRACT

When acoustic scattering estimates are desired from atmospheric regions containing fully developed isotropic homogeneous turbulence, scattering formulas based upon statistical representations of the turbulence well represent the experimental results. However, there is a class of battlefield scenarios where these provisos of fully developed, isotropic, and homogeneous sometimes do not apply. The example of this class that is most familiar is that of source and detector near the ground. At ground level, the wind velocity is zero, while at altitude it is not. Thus a gradient of wind velocity exists. There exists often a temperature gradient caused by heating or cooling of the air by contact with the ground. These gradients are recognized in propagation codes by modeling the atmosphere as stratified with each strata bounded by planes parallel to the assumed flat ground. The anisotropy of the atmosphere near the ground recognized in propagation codes carries over into the generation of turbulence. The above discussion leads to the conclusion that anisotropy in turbulence is to be expected in scenarios played out near the ground, scenarios common to Army operations. The understanding that high sound levels in shadow zones (those regions in an acoustical field in which no sound can reach if the field is determined by ray theory) is caused by scattering from turbulence is very important. This importance arises from the possibility that shadow zone sensors may be used to achieve passive non-line-of-sight detection of enemy assets. This paper unites the above considerations by calculating the shadow zone signal level for a representative battlefield scenario using a structural model of turbulence.

1. INTRODUCTION

Acoustics has become prominent in recent years as a means for Army units to detect and locate enemy assets on the battlefield. Increased understanding of atmospheric effects on acoustic propagation has fostered development of propagation models of increasing sophistication as more and more atmospheric effects are included. While the atmosphere is much too complex to model exactly, a number of effects can now be modeled that greatly increase the accuracy and reliability of acoustic signal level predictions. Among those effects that can be included in propagation models are temperature gradients, wind speed gradients, molecular absorption, ground reflections, and certain diffraction effects. This

paper is concerned with the effect of scattering from turbulence on acoustic propagation. Although the inhomogeneities in atmospheric propagation characteristics are relatively small, acoustic signals scattered from turbulent regions can be detected and used for tactical purposes. Section 2 discusses the interplay between average atmospheric properties and the small-scale deviations from these averages caused by turbulence, with a view to defining the problem that must be solved to include scattering from turbulence in acoustic propagation codes. Section 3 discusses two models of turbulence--the statistical model and the structural model. Section 4 discusses recent modifications to a widely used propagation model that allow incorporation of structural model features, and section 5 summarizes the matters covered in the previous sections.

2. ACOUSTICAL PROPAGATION ON THE BATTLEFIELD

The subject of shadow zones is connected closely to the subject of scattering from turbulence. Shadow zones are those regions of the atmosphere where acoustical signals could not penetrate if they traveled as light beams travel. In a uniform atmosphere, light beams travel in straight lines, which results in the region behind obstacles, such as a mountain or a ridge, being a shadow zone. This situation is indicated in figure 1, where a typical Army scenario is depicted. On the left, a source S is depicted near the ground at x position zero. On the right, a detector is depicted, also near the ground at x position 10,000 m. The lines marked SB and DB are drawn from S and D through the top of a 250-m-high ridge that is not shown located at x position 5000 m. The line SB marks the shadow zone boundary for the sound emanating from the source. The detector is thus in a geometric shadow zone. Above the ridge location, a turbulent region is depicted by a stylized pattern. Sound from the source reaches the detector by being scattered from the inhomogeneities in the turbulence. The line DB is the lower limit of the region from which the detector can receive scattered energy according to ray theory. The line DT indicates the upper limit of the field of view of the detector. In most instances, this limit is not well-defined. A similar line ST defines the upper limit of the radiation pattern of the source. These four lines when extended to appropriate surfaces enclose an enormous volume from which radiation can be scattered into the detector. How much radiation is scattered from each subelement of this scattering volume depends upon the distances to the source and detector, the angle between the propagation and scattered directions (the scattering angle), and the scattering properties of the turbulence that exists at that particular location. The scattering angle in this scenario varies from around 6 degrees for the region just above the ridge to almost 90 degrees for the regions just above the source and just above the detector. The scenario of figure 1 illustrates the importance of scattering from turbulence. The source S can be detected by the detector D even though there is no line-of-sight path from D to S.

A geometric shadow zone exists even in a homogeneous atmosphere and certain atmospheric conditions can cause shadow zones even in flat terrain. These conditions involve a sound speed gradient wherein the sound speed is lower at altitude than at ground level, which causes phase fronts of waves to be retarded at altitude and result in ray paths that curve upward. Since sound speed is a function of temperature, a negative temperature gradient can cause a shadow zone (figure 2). Figure 2 shows the limit ray path for a constant negative sound speed gradient. In this case, the ray paths are circles whose center is high above the figure and which pass through the source location. The limit ray is the circle that passes through the source and is tangent to the ground as shown. The region on the right between the limit ray path and the ground is the shadow zone.

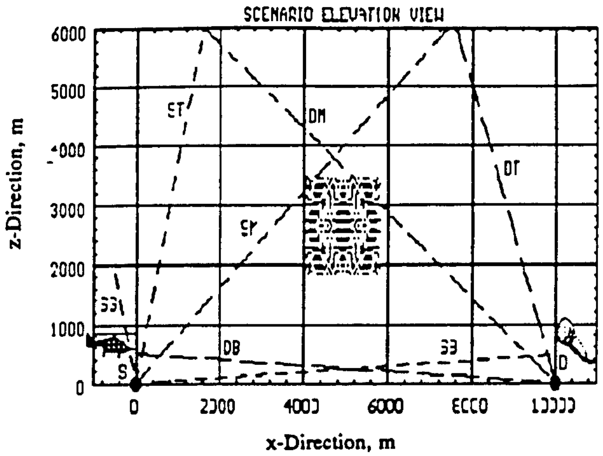

Figure 1. Typical Army scenario.

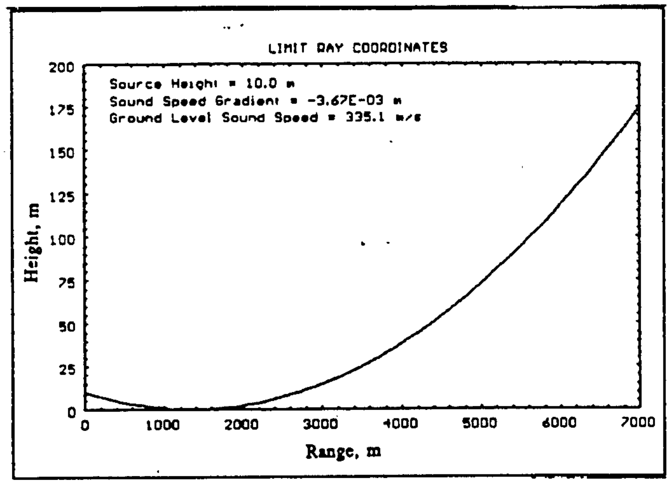

Figure 2. Limit ray path.

A third type of shadow zone is that caused by wind speed gradients. If a component of the wind blows from the detector towards the source, the net speed of sound aloft is lower than at the ground because the wind speed is zero at ground level. A similar situation to that of figure 2 is created if the wind speed gradient is constant and negative.

Propagation codes currently are able to model the effects of flat terrain only. Geometric shadow zones cannot, therefore, be modeled. These codes can, however, model both temperature and wind-induced shadow zones over flat ground. The atmospheric property variability with altitude (variation with either horizontal coordinate cannot be handled either, as a general rule) is approximated by partitioning the atmosphere into a number of layers bounded by planes parallel to the ground. The atmospheric, and therefore the acoustic, parameters are constant within any particular layer. Propagation codes are also currently limited to two dimensions: horizontal distance (x) and vertical distance (z). Some codes, notably the parabolic equation (PE) code, can model turbulence by including a phase screen onto which a random phase is induced at certain locations in the propagation path. The most mature code, called the fast field program (FFP), cannot model turbulence effects. Finally, current propagation codes can only model isotropic sources, those sources which emit radiation equally in all directions. Because FFP is a full wave code (modeling waves traveling in the plus x as well as the minus x direction) and PE is not, the problem is to introduce turbulence effects into a new version of FFP.

3. TURBULENCE MODELS

At this point, it is appropriate to examine some of the experimental evidence associated with the understanding of acoustic signals in shadow zones. The accepted nature of this understanding is represented by relative sound level graphed in figure 3 (Gilbert 1990). The relative sound level is the actual sound level at the field point increased by the spherical spreading and attenuation losses. It thus represents the signal loss not due to spherical spreading and molecular absorption. The graph is representative of evidence from many experiments. The curve shows that near the source in region 1 the relative sound level is constant. For frequencies with negligible absorption, the actual signal

experiences only spherical spreading loss, which goes as one over the distance squared. In region 2, the sound level falls off rapidly as is expected when passing into the shadow zone. This rapid falloff does not continue; but in region 3 the relative sound level is constant, again indicating that the actual signal falls off according to the inverse square law. In region 3, the relative sound level is indicated to be -25 dB. This value is something of an average, the range being between -20 dB and -30 dB (Gilbert 1990). An actual case is shown in figure 4 (Gilbert 1990) where theoretical results are superimposed upon measured results. The connected dots are the experimental data; the solid curve is the authors' calculation using the PE model coupled with a phase screen turbulence model. The dashed line was calculated with PE without turbulence. The rapid falloff of the latter is readily apparent. The significance of figure 4 is that sound levels are higher than expected in refractive shadow zones and turbulence scattering is the accepted cause of these high levels. One would expect that a similar anomalously high sound level would exist in a geometric shadow zone near the ground for a source near the ground.

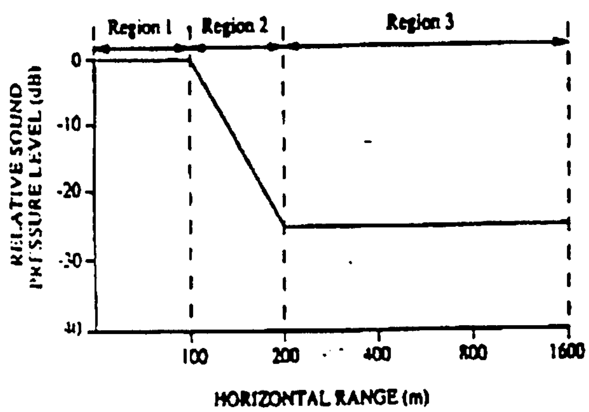

Figure 3. Experimental shadow zone levels.

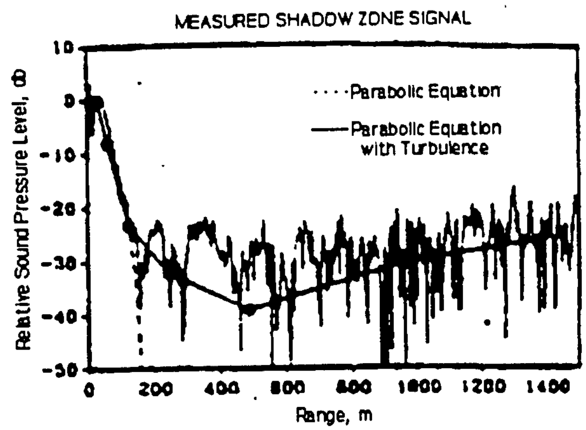

Figure 4. Experimental and theoretical shadow zone levels compared.

The anisotropy of the atmosphere near the ground recognized in propagation codes carries over into the generation of turbulence. Figure 5 illustrates the vertical variation of the velocity and temperature structure constants with altitude based upon experimental data (Brown 1976). In the figure, C_v^2 is a measure of the strength of the velocity turbulence and C_T^2 is a measure of the temperature turbulence. As a further illustration of the anisotropy of turbulence over flat ground, curves for measured velocity spectra (Kaimal 1976) are reproduced in figure 6. The parameters on the curves are height ratios. The wider variability of the w component (the vertical component) is clearly represented. That the curves for lower heights peak at higher frequencies indicates that the largest structures are smaller at lower heights.

The anisotropy of turbulence over flat terrain (figures 5 and 6) will be reinforced when complex terrain is included in the scenario. For instance, when wind flows across a ridge, the structure of the inhomogeneities will contain horizontal roll vortices if the wind velocity is high enough. This flow will be superimposed upon the turbulence already present. The above discussion leads to the conclusion that anisotropy in turbulence is to be expected in scenarios played out near the ground, scenarios common to Army operations.

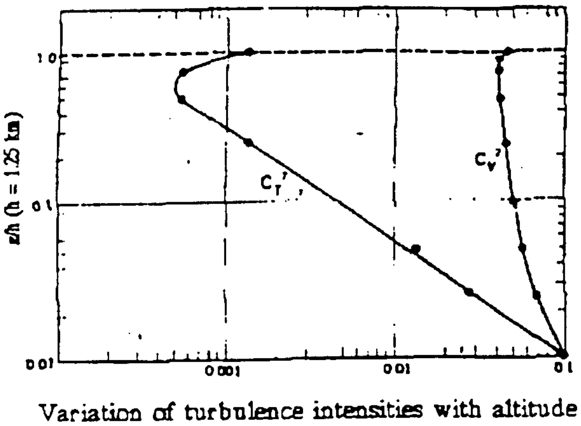

Figure 5. Experiment based structure constant variation.

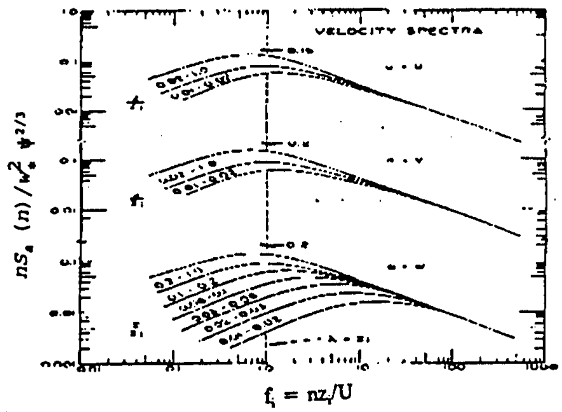

Figure 6. Velocity spectra for different heights.

Previously, atmospheric turbulence models have been based upon the energy cascade hypothesis, which states that energy enters a turbulent region primarily as large eddies. The size of the large eddies is termed the upper-scale limit. The energy in the large eddies is transferred to smaller eddies in such a manner that the energy content of all the eddies in a size class remains constant. The flow of energy is absorbed by viscous forces in the smallest eddies. The size of the latter is termed the lower-scale limit. These few assumptions are sufficient to allow numerous inferences about the properties of the turbulence and its influence on waves that propagate through the region. It is not necessary to know the parameters of the eddy structure. The results that are obtained are dependent upon a probability relationship for structure sizes and an assumption that the turbulent region is isotropic and homogeneous. Isotropic means that the probability distribution is the same for any direction. Homogeneous means that the probability distribution is the same for any point. This model is called the statistical model because it is dependent upon a probability distribution. An important relation (Tatarskii 1971) that comes from this model is an expression for the acoustic scattering cross section that is given in equation (1). In the equation k is $2\pi/\lambda$ and θ is the scattering angle. The important point in

$$\sigma(\theta) = \left[\frac{0.38k^{1/3}[\cos(\theta)]^2}{(2\sin(\theta/2))^{11/3}}\right]\left[\frac{C_v^2}{c_0^2}(\cos(\theta/2))^2 + 0.13\frac{C_T^2}{T_0^2}\right] \qquad (1)$$

equation (1) is the sine factor in the denominator. It is raised to a power that is almost 4, so that for small angles it drives the cross section towards infinite size. Apart from the difficulty of dealing with the infinity, the equation indicates that scattering in the forward direction is dominant, which says that scattering is great for turbulence just over the central ridge in figure 1.

To get a better handle on acoustic scattering, Goedecke (1992) developed a formula for the cross section by using the structural model for turbulence. The structural model takes the eddy idea of the statistical model a step further by assuming a definite form for the velocity variation within the eddy. Figure 7 shows the scattering efficiency Q for a velocity eddy as a function of scattering angle. An eddy is a rotating mass so that it has a rotation axis that can have an arbitrary orientation. A turbulent region will have eddies of all different sizes and orientations. By making certain assumptions about the number concentrations of the eddies of the various size classes, one can perform summing over the size classes and integrating over all orientation angles. When this process is done, the result matches the statistical model result over the size range between the upper- and lower-scale sizes as it should. Q is the scattering cross section divided by the physical cross section and is therefore dimensionless and is a function of the orientation. In figure 7, Q has been averaged over orientation angles. The surprising feature in figure 7 is the zero cross section obtained for scattering in the forward direction as contrasted with the value obtained from the statistical model. The predominant scattering at 45 degrees is also an interesting feature.

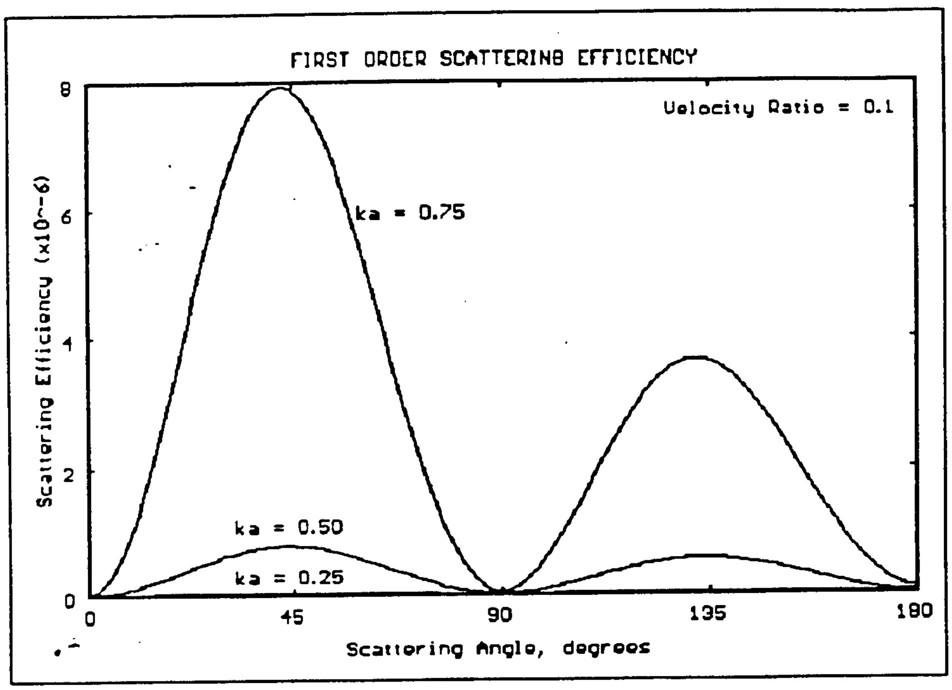

Figure 7. Scattering efficiency for a velocity eddy.

The discrepancy between the scattering formulas developed from the statistical model and the structural model has not been fully resolved. However, for our immediate purposes, we can say that acoustic scattering from turbulence is not isotropic even under the assumption that the turbulence itself is isotropic and homogeneous. The next section recounts what has been done to accommodate this anisotropic property of acoustic scattering in a propagation model.

4. ACOUSTICAL MULTISTREAM PROPAGATION PROGRAM

In accord with the anisotropic inhomogeneous properties of turbulence near the ground confirmed by the experimental data illustrated in figures 5 and 6, a structural model of turbulence was chosen to incorporate into FFP. A structural model implies a sum over turbule sizes, whereas FFP currently calculates for a single source. The plan was to calculate the signal level at all scatterer locations that resulted from a true source, and then do a number of passes where the scatterers were thought of as sources whose strength varied as the direct signal at the scatterer location. The acoustical field in the region of interest would be preserved for each "source" and the results summed coherently to arrive at the final result. Another feature of FFP was to be addressed differently. FFP calculates the field for one detector height only. Knowledge of results at a number of heights is desirable for one to adequately study the acoustical field. In the case of a two-dimensional calculation such as is possible with FFP, knowing the field at enough detector heights will allow one to display the results as a contour plot in the x-z plane.

Since the new model was to be a major addition to the capability of FFP, an entirely new name was used. The new model is called the Acoustical Multistream Propagation Program (AMPP). AMPP contains FFP as a subroutine as shown in the block diagram of figure 8. Subroutine FFP is slightly different from other versions in that the parameter input code has been extracted and moved to subroutine INPUT. Other than the input code, the usual FFP routines are contained within the block surrounded by the short dashed line. This block is called once for each source-detector height combination for a total of NSRC*NDET as indicated. The block within the long dashed line is the usual FFP summation over panels as also indicated. Subroutine EXTENDR accomplishes data archive and management. A separate output file of sound pressure levels for a single detector height for each source is created. Subroutine XTRASC extracts data from these output files to create an array suitable for generating a contour plot. A scatterer is represented as a source and detector pair that have the same coordinates. Subroutine FFP is not called in this case, only the amplitude and phase of the pressure wave at that location being preserved. This value is used later in subroutine XTRASC along with adjustment for the scatterer cross section.

The following figures illustrate AMPP results. Figure 9, a contour plot generated by data from AMPP, is for a single source at 10 m height at zero range operating at 170 Hz. The atmosphere of the plot has a uniform negative sound speed gradient. The heavy line across the center of the diagram is the limit ray path for the chosen conditions. It parallels the -90 dB contour. The low sound levels in the shadow zone are apparent. The contour plot of figure 10 is for a scatterer at height 744 m at a distance of 5000 m and has not been adjusted for source to scatter loss. The interference between the primary wave and that reflected from the ground produces the striations in the sound field.

The combined fields shown in figures 9 and 10 are shown in figure 11 after accounting for source-scatterer loss. The signal fill in the shadow zone is apparent. The calculation for figure 11 is simplified for illustrative purposes. The cross section of the scatterer was chosen to give approximately the signal level shown in figure 5. The reason for this choice is discussed in the next paragraph.

Acoustical Multi-stream Propagation Program

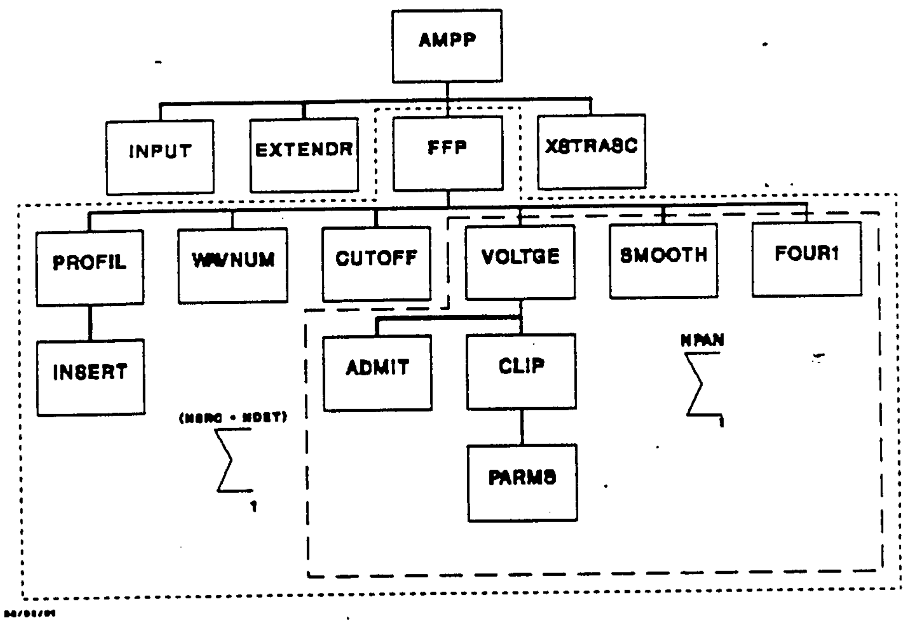

Figure 8. AMPP block diagram.

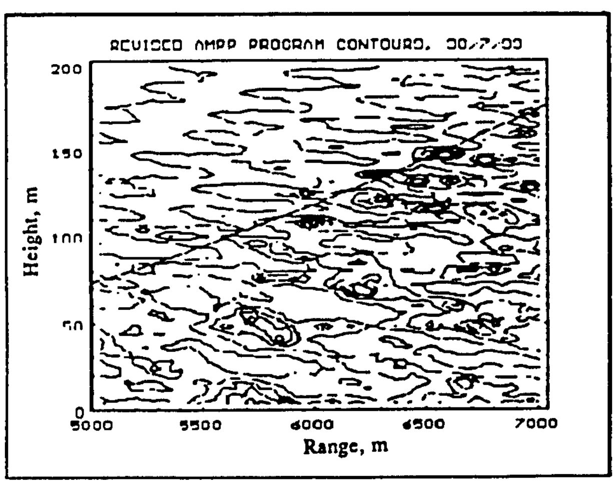

Figure 9. AMPP results for an upward refracting atmosphere.

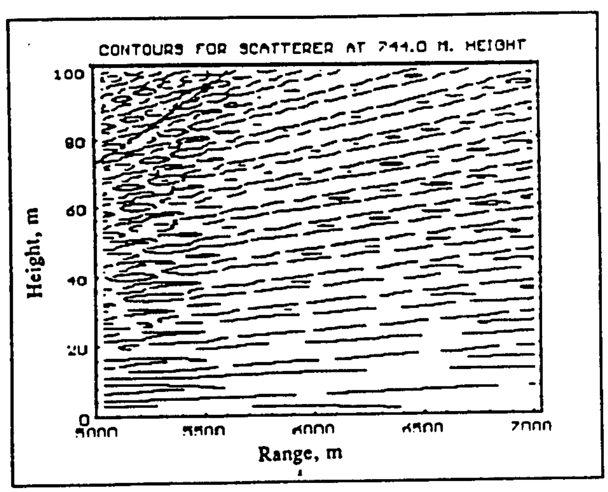

Figure 10. Scattered field.

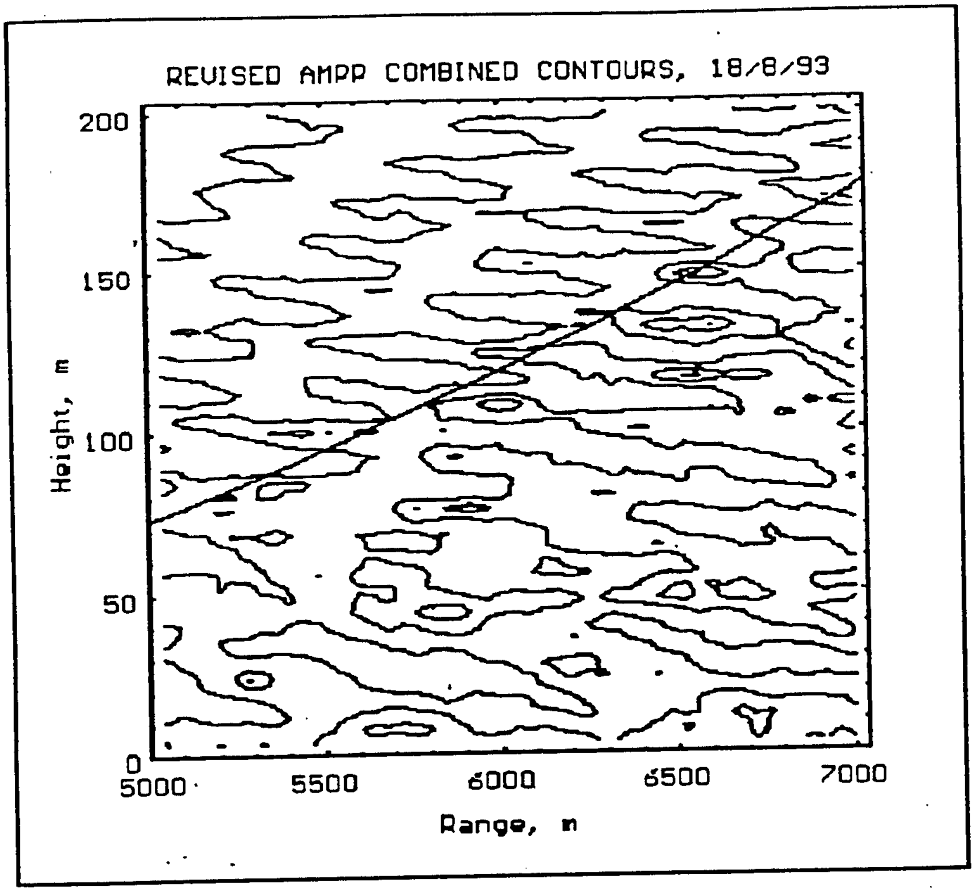

Figure 11. Combined direct and scattered fields.

The implementation of AMPP is incomplete as reported here in that the method for effecting the anisotropic scattering pattern of equation (1) or figure 7 has not been exercised. The scattered pattern of figure 10 is for an isotropic or spherical scatterer because that is the only type of "source" that FFP/AMPP can model. The plan is to approximate a known scattering pattern such as that of figure 7 by a multipole expansion. The curves of figure 7 consist of a quadrapole field with a superposed function that emphasizes the forward portion as the turbule size increases with respect to the wavelength. This pattern can be separated into its multipole components. Then these multipole components can be approximated by appropriately spaced and phased monopole (spherical) sources. This plan is being carried out at the present time, but no results are yet available.

5. SUMMARY

The significant points made in this paper are summarized here. Acoustical signals in shadow zones are a possible non-line-of-sight detection means on the battlefield. Shadow zone signals are caused by scattering from turbulence, and the structural model of turbulence permits analysis of anisotropic inhomogeneous turbulence effects. Anisotropic scattered fields can be approximated by a multipole expansion by using a number of spherical sources. The AMPP augmentation of FFP will calculate

shadow zone fields in the x-z plane for a layered atmosphere that contains a superposed field of anisotropic scatterers. The summation capability of AMPP carries out the accumulation of the multipole fields to achieve the anisotropic scattering patterns.

REFERENCES

Brown, E. H., and S. F. Clifford, 1976, "On the Attenuation of Sound by Turbulence," J. Acoust. Soc. Am., 60(4):788-794.

Gilbert, K. E., R. Raspet, and X. Di, 1990, "Calculation of Turbulence Effects in an Upward-refracting Atmosphere," J. Acoust. Soc. Am., 87(6):2428-2437.

Goedecke, G. H., 1992, Scattering of Acoustical Waves by a Spinning Atmospheric Turbule, CR-92-0001-2, U.S. Army Research Laboratory, White Sands Missile Range, NM 88002-5501.

Kaimal, J. C., J. C. Wyngaard, D. A. Haugen, O. R. Coté, S. J. Caughey and C. J. Readings, 1976, "Turbulence Structure in the Convective Boundary Layer," J. Atmos. Sci., 33:2152-2169.

Tatarskii, V. I., 1971, The Effects of the Turbulent Atmosphere on Wave Propagation. TT-68-50464, National Technical Information Service, Springfield, VA 22161.